Ces schémas sont ceux de Mme Palanque-Delabrouille au cours de son exposé sur DESI.
Si ma reproduction la gêne pour des raisons de droit, je les supprimerai aussitôt.
GT

DARK ENERGY SPECTROSCOPIC INSTRUMENT

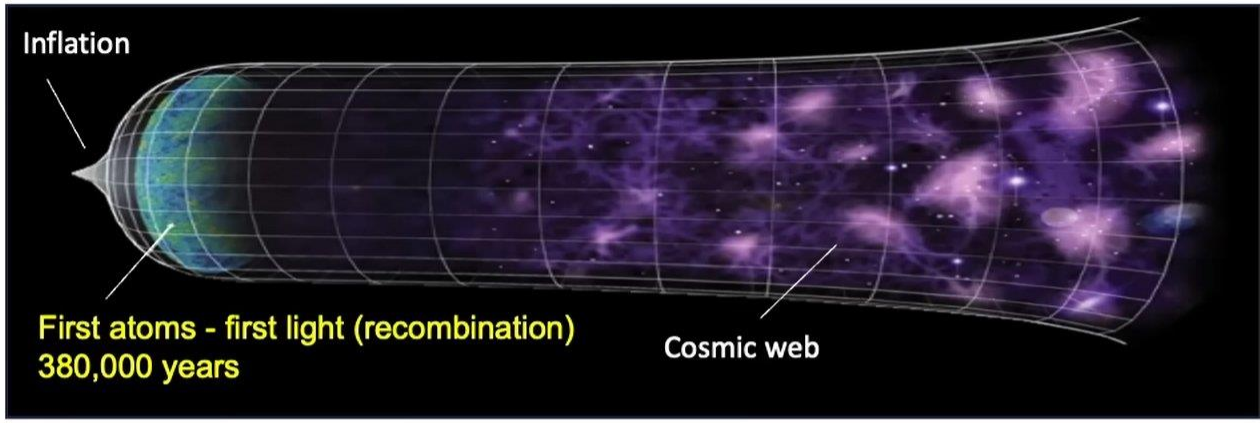
U.S. Department of Energy Office of Science

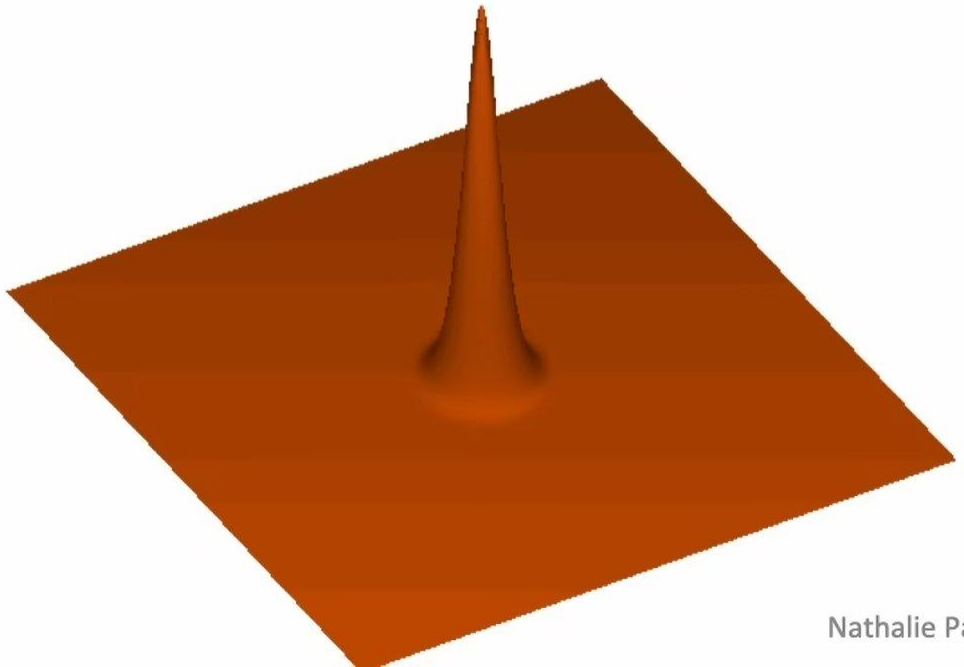
Baryon Acoustic Oscillations (BAO)

Propagation of baryon-photon over-density sound waves in primordial plasma

At recombination (z~1100): $p + e^- \rightarrow H$

- Baryons decouple from photons
- Waves stall



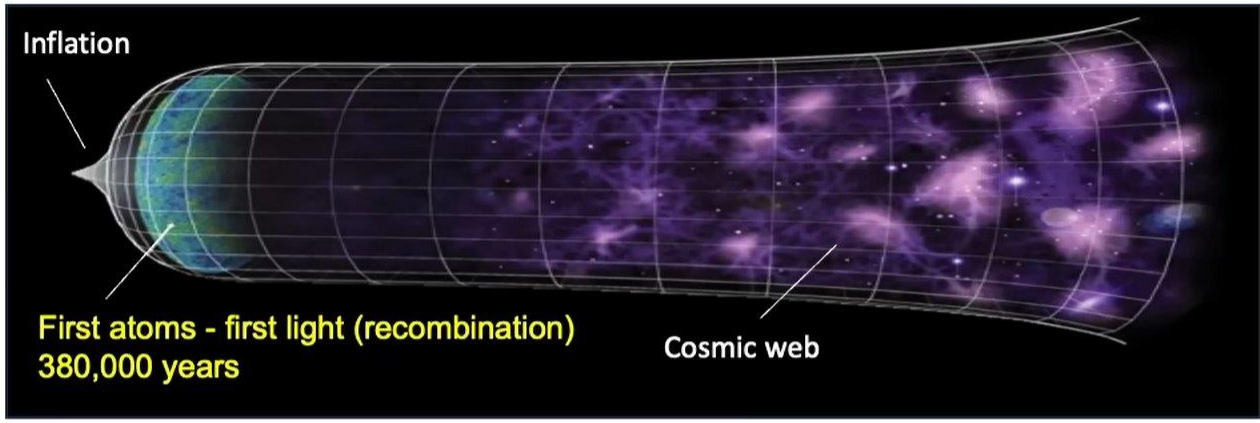


Residual spherical shell ⟶ Peak in clustering of matter

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Baryon Acoustic Oscillations (BAO)



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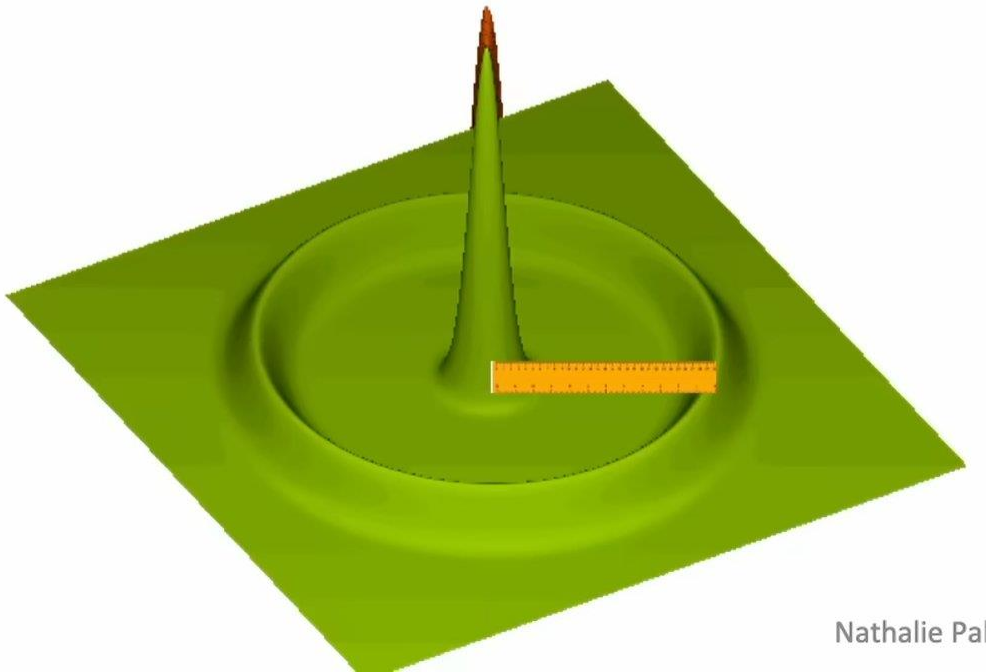


Residual spherical shell ⟶ Peak in clustering of matter

Size of feature = distance sound wave traveled

Preferred 3D scale $r_s \sim 150$ kpc (at recombination)
$r_s \sim 150$ Mpc (today) ~ 450 million l.y.

DARK ENERGY SPECTROSCOPIC INSTRUMENT

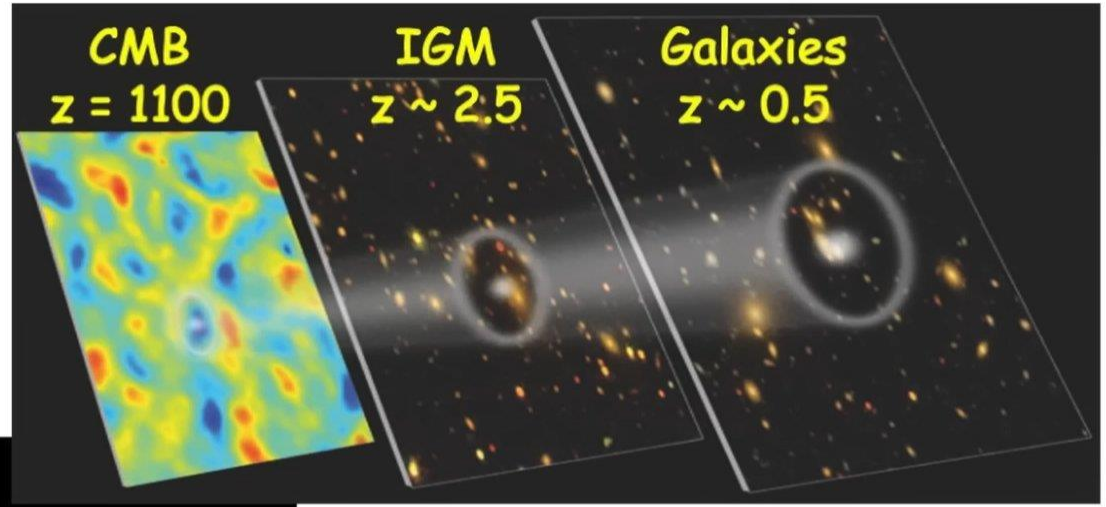
U.S. Department of Energy Office of Science

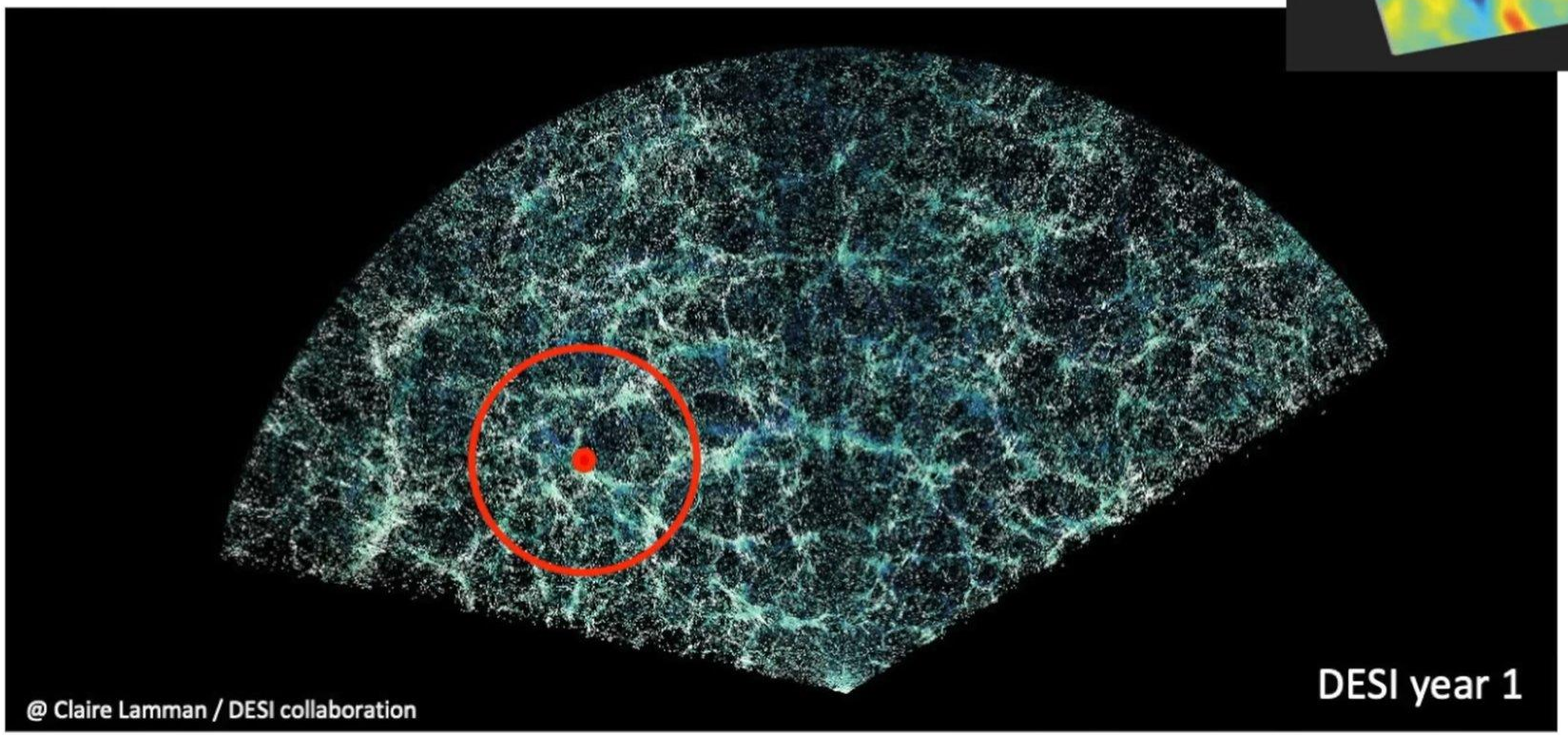
Baryon Acoustic Oscillations (BAO)

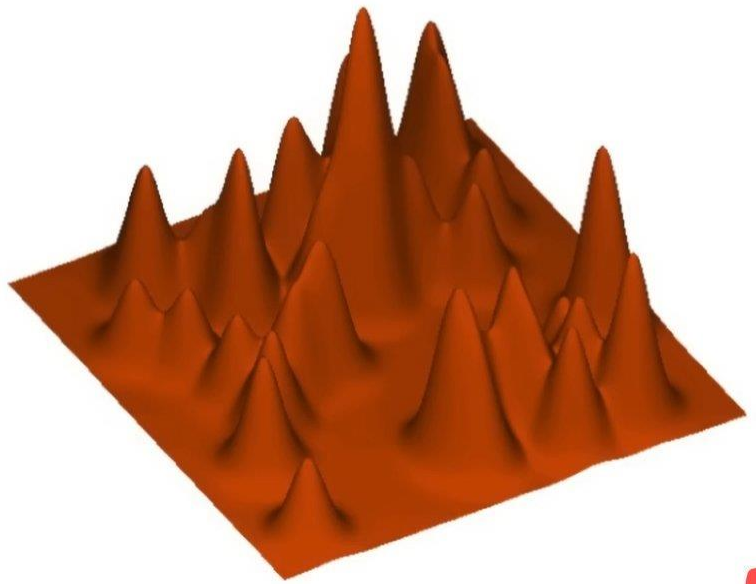
Imprint of primordial fluctuations

↓

Standard Ruler to measure distances







DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

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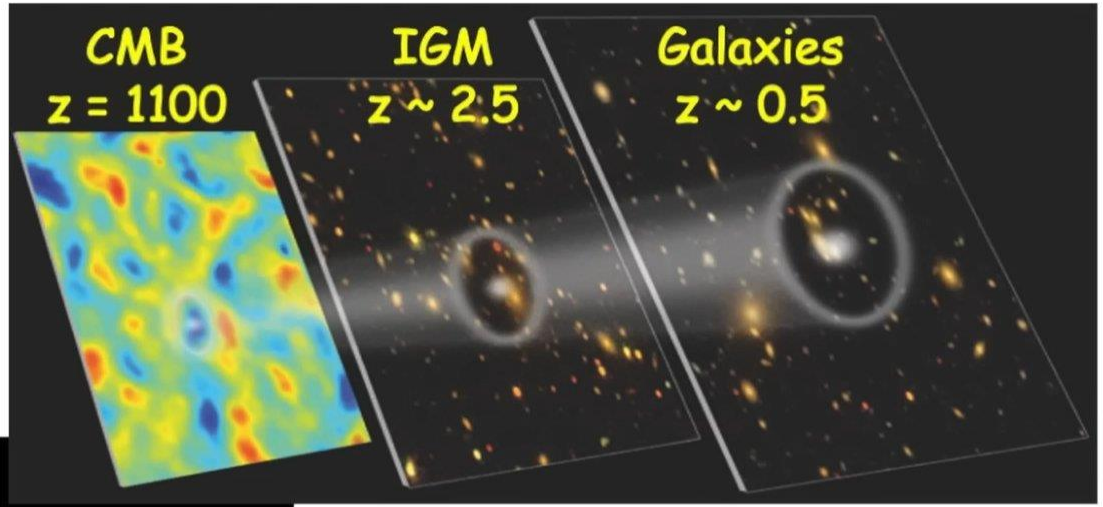

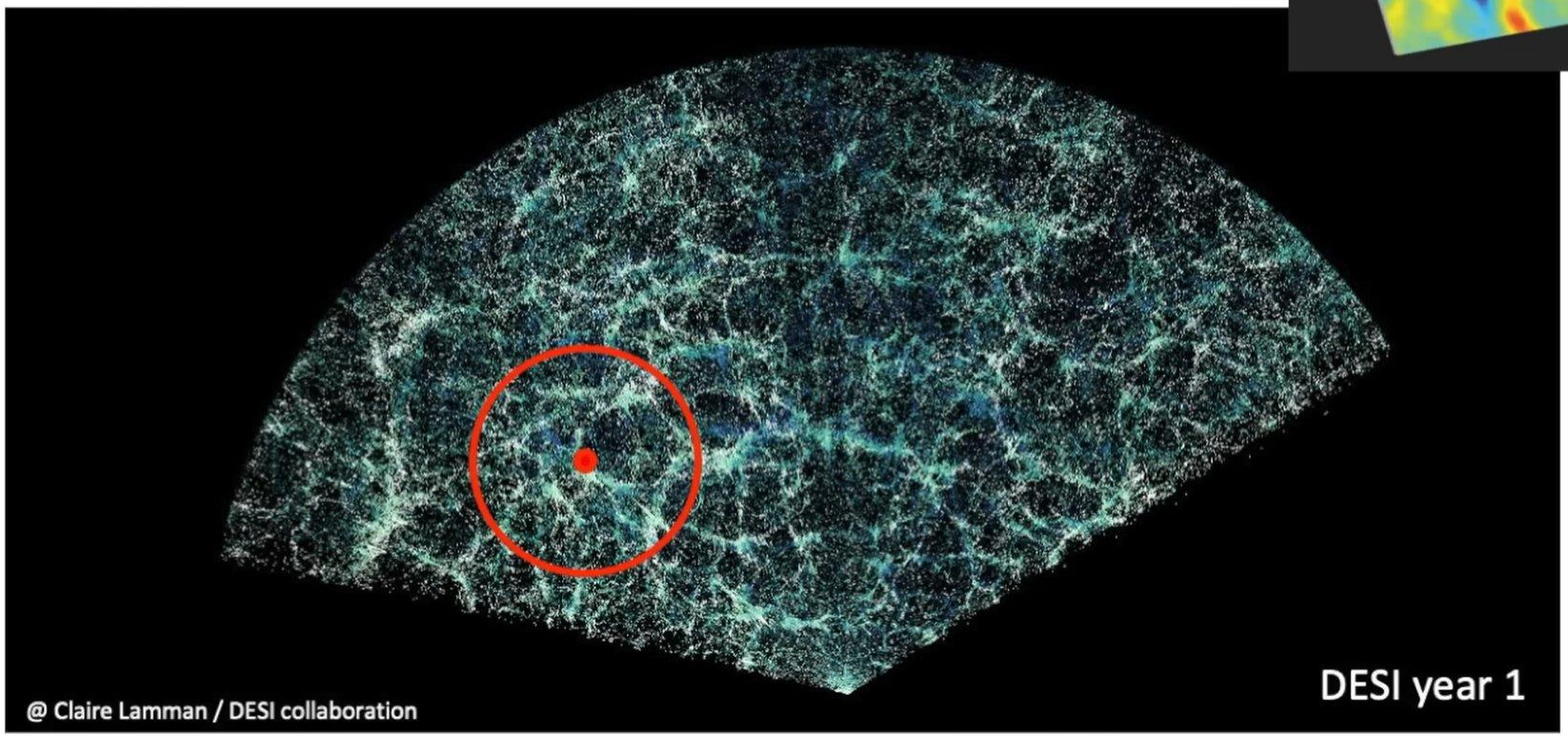

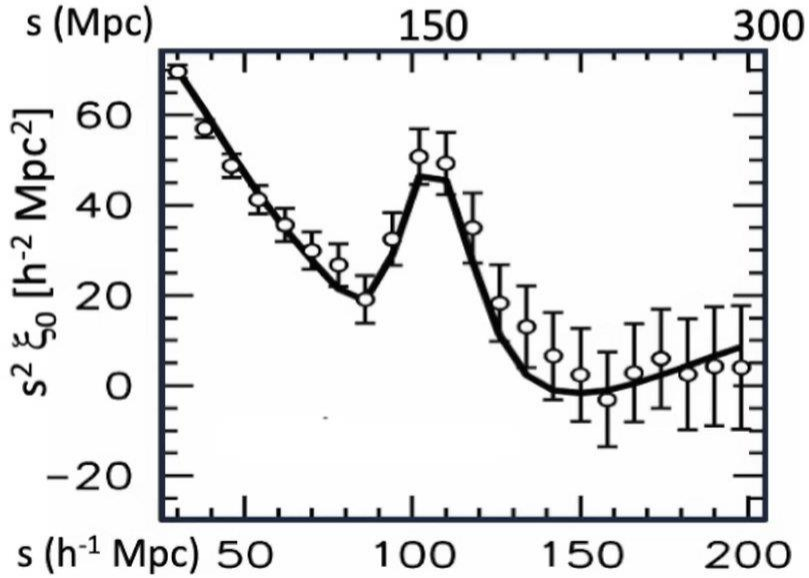

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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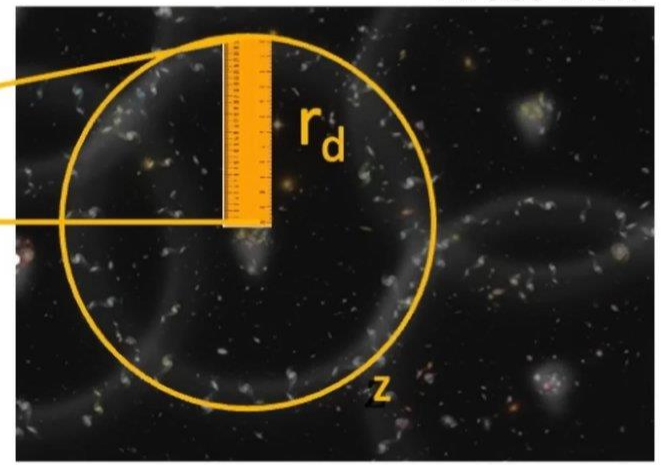
The BAO standard ruler

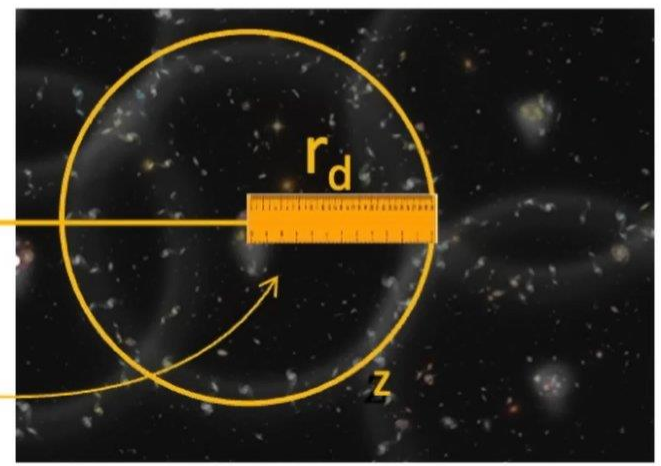
$\theta_{BAO} = r_d / D_M(z)$

Angular diameter distance

Artist view

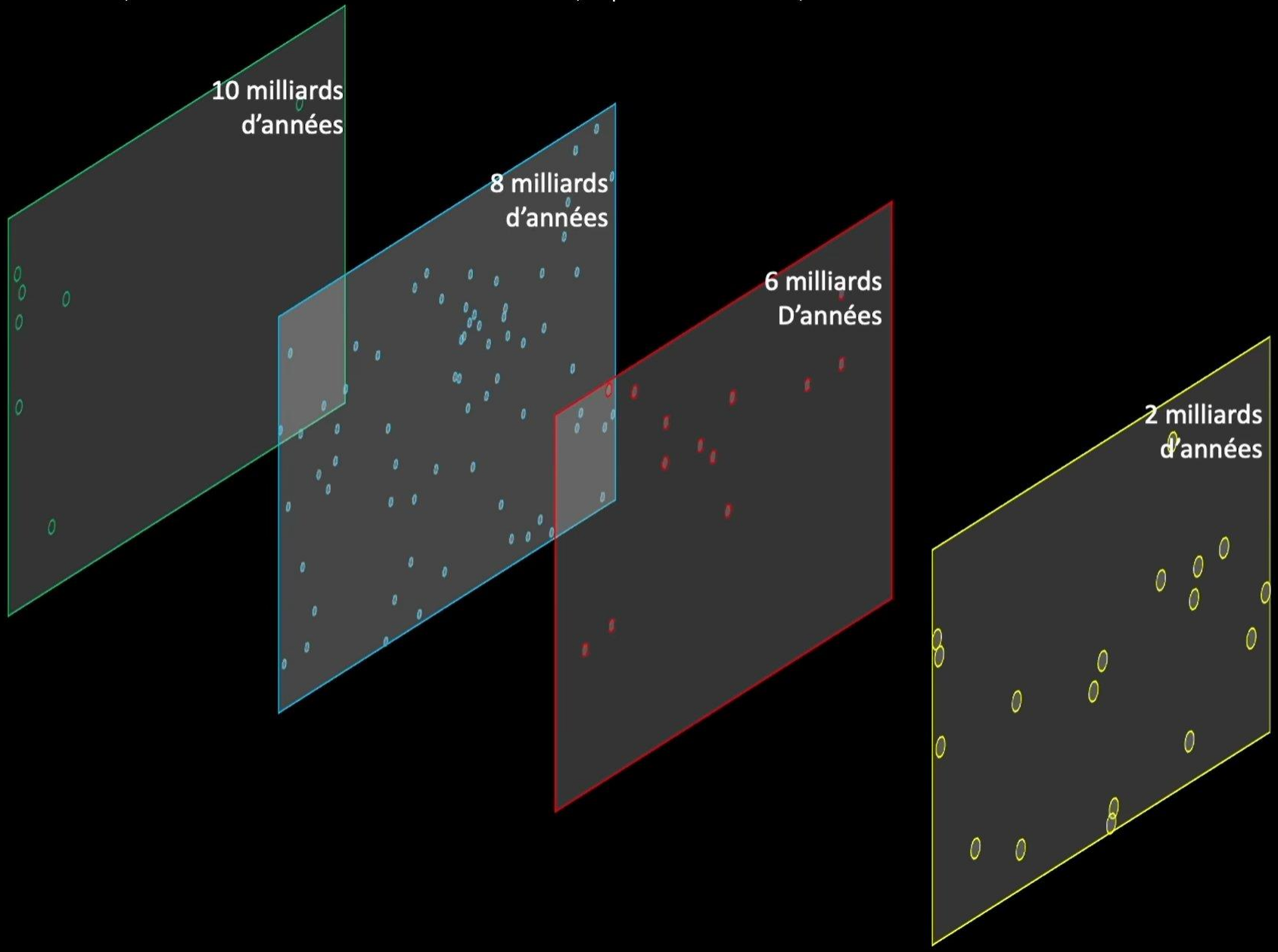


Hubble parameter



$\delta z_{BAO} = r_d H(z) / c$

$D_M(z)$ and $H(z)$ encode expansion history of the Universe


10 milliards
d'années
8 milliards
d'années
6 milliards
D'années
2 milliards
d'années

SUBSCRIBE

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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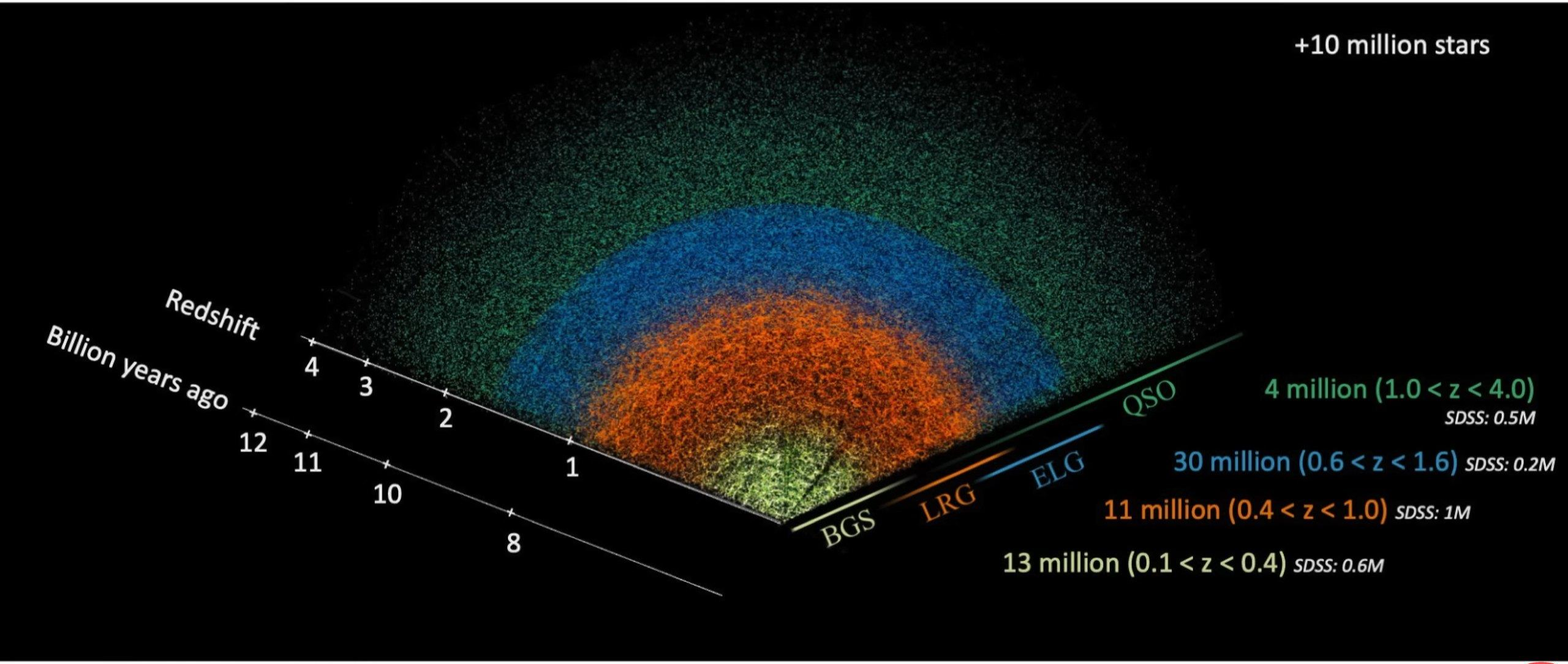
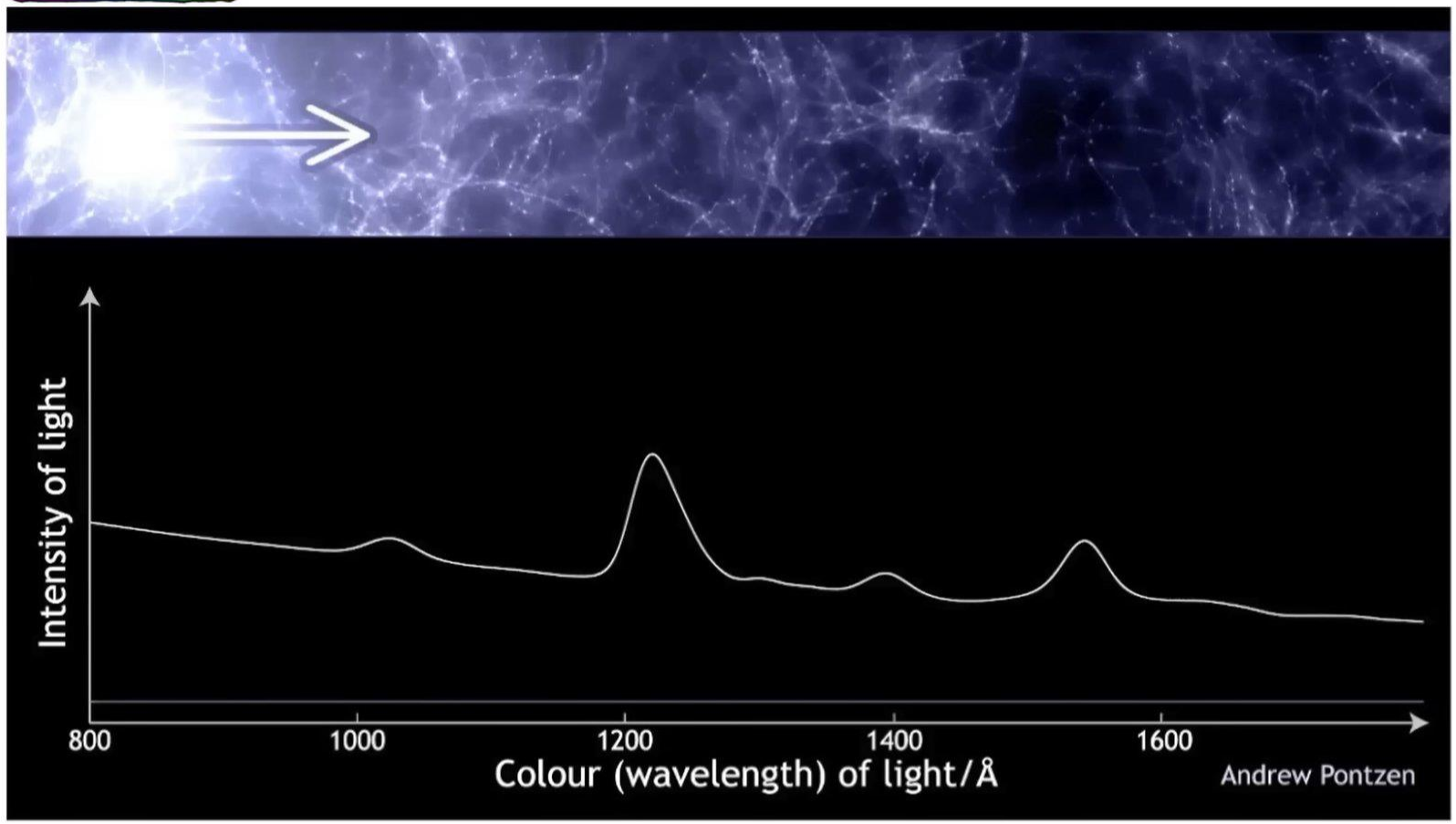
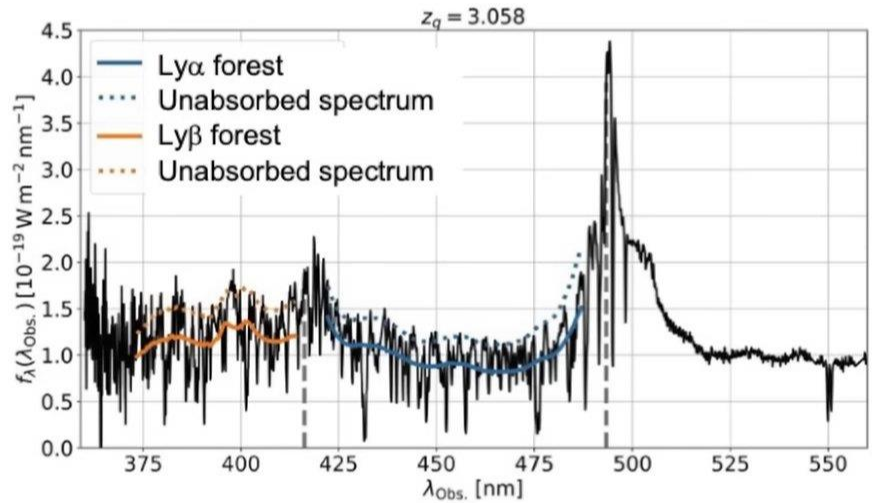
DESI targets: 60+ million galaxies and quasars



DARK ENERGY SPECTROSCOPIC INSTRUMENT

The Lyman-α Forest at z>2.1





$$F = e^{-\tau}$$

$$\tau \propto n_{HI}$$

- Quasars visible to high redshift (z ~ 5)
- Absorption of quasar liht by neutral H in IGM
- Transmitted flux fraction F: proxy for matter (neutral H) density

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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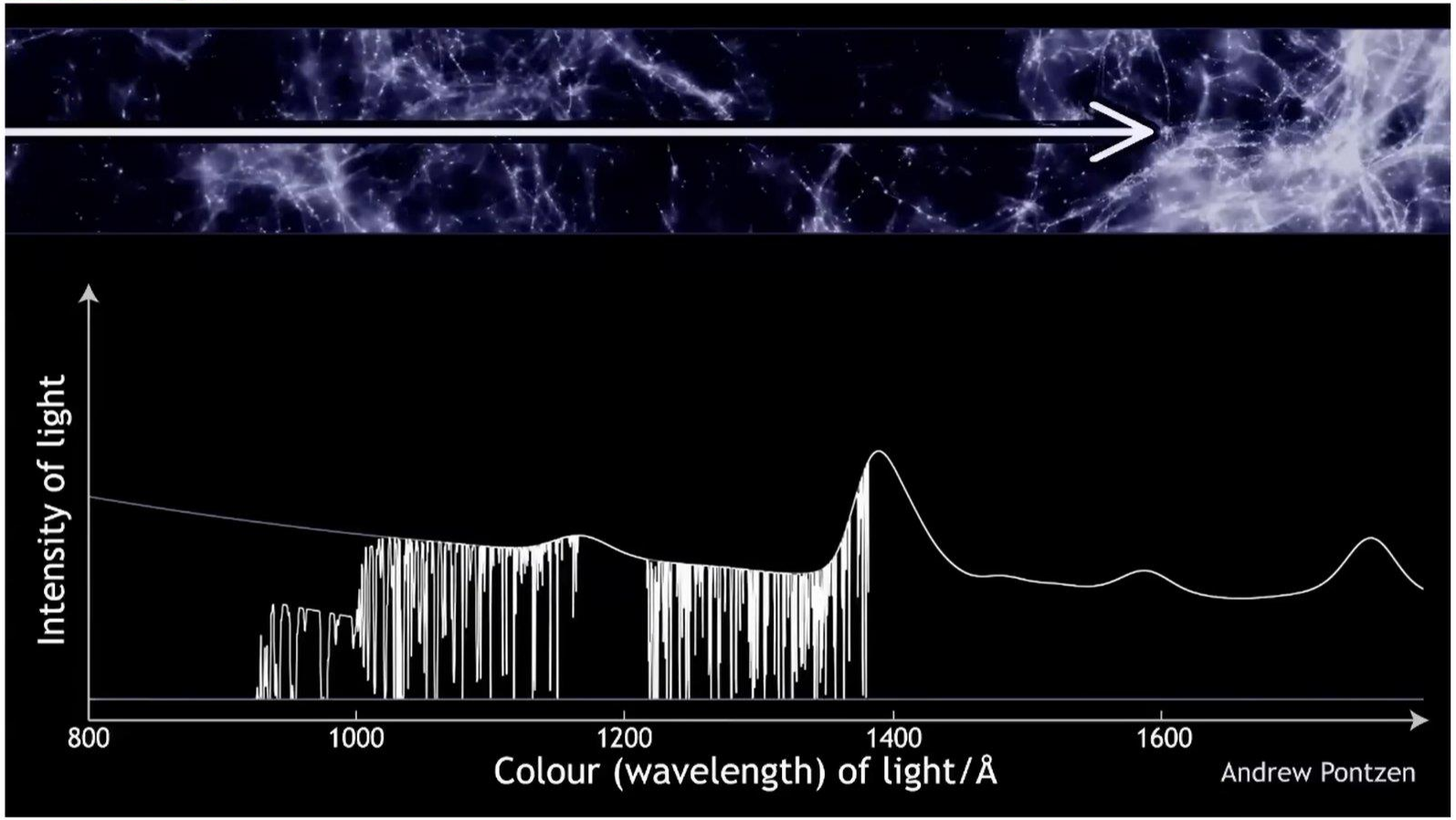

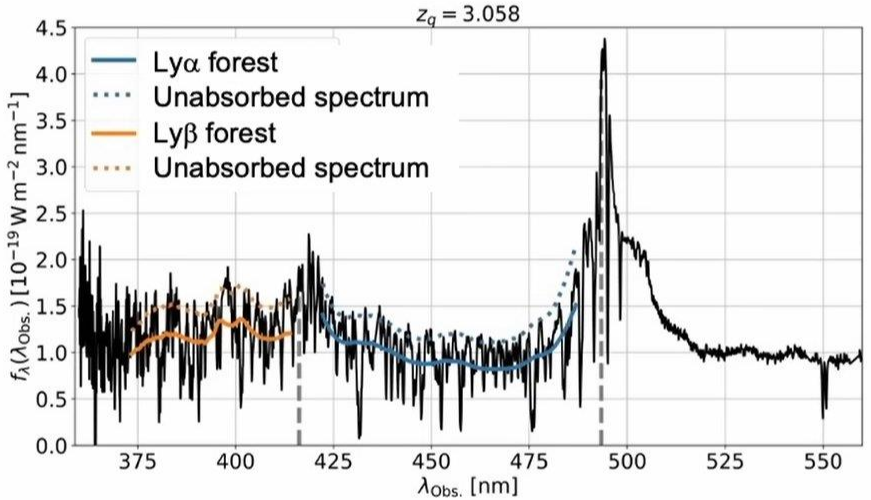

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DARK ENERGY SPECTROSCOPIC INSTRUMENT

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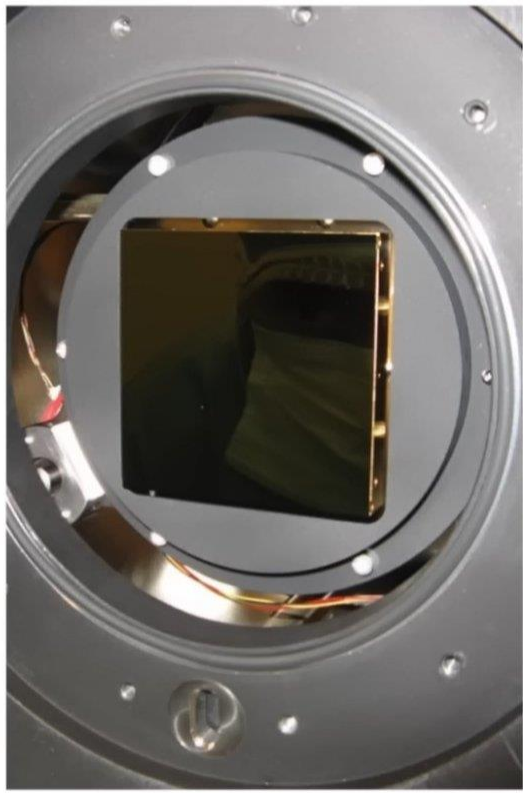
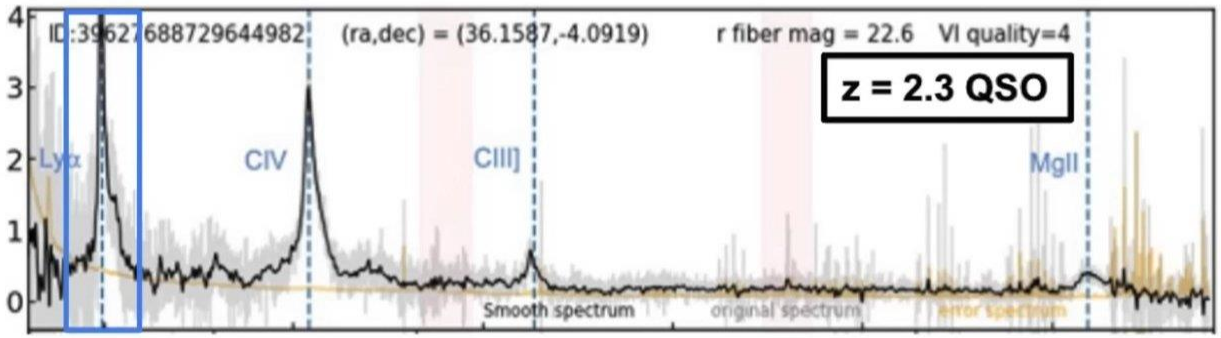
DESI instrument

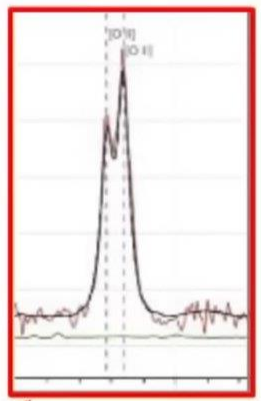
10 3-band spectrographs [360nm – 980nm]

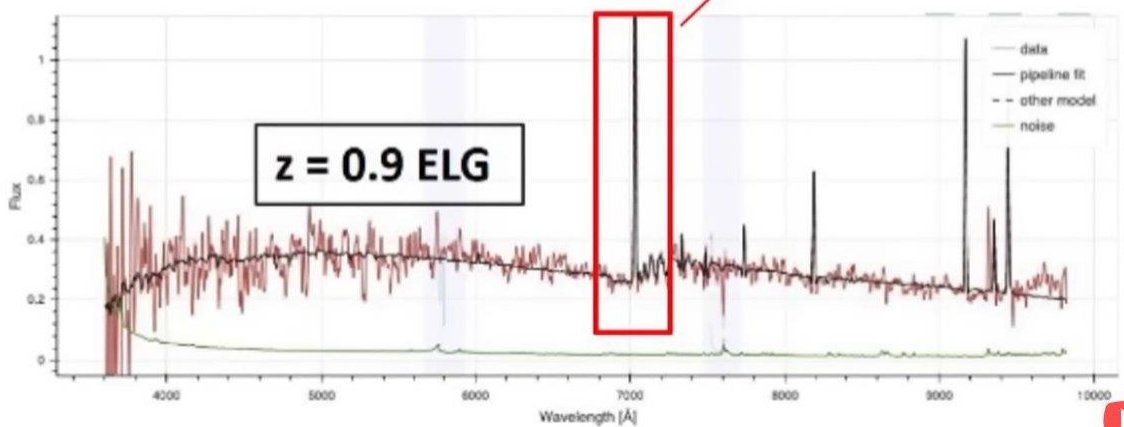


Lyα λ121.6 nm
down to z = 2.0



[OII] λ373 nm
up to z = 1.6





$$z = \frac{\lambda - \lambda_0}{\lambda_0}$$

What can cause accelerated expansion?

1/ Cosmological constant

2/ New component (“dark energy”)

3/ Modifications to the laws of General Relativity

$$G_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4}\, T_{\mu\nu}$$

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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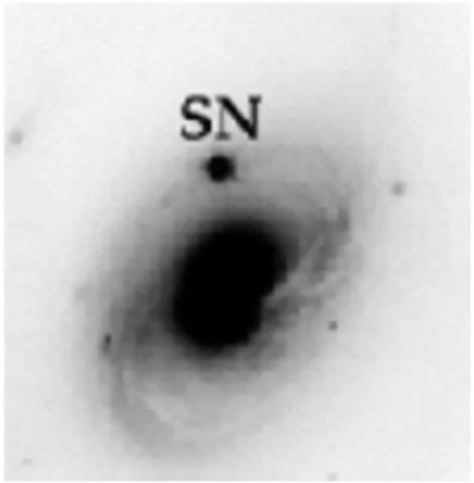
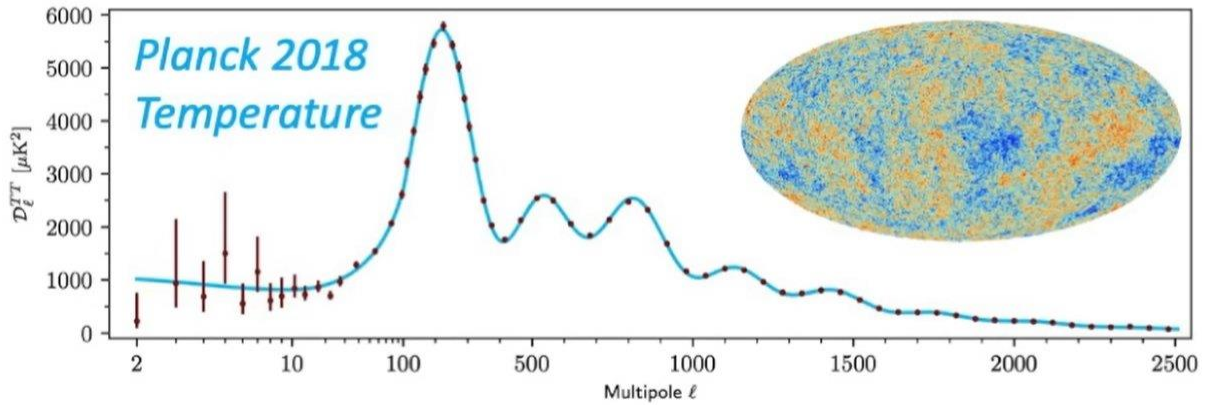
1/ Dark Energy = cosmological constant?

- "a-la-Einstein" approach
- Simplest explanation (a unique parameter Λ)
- In agreement with most observations of past 20 years

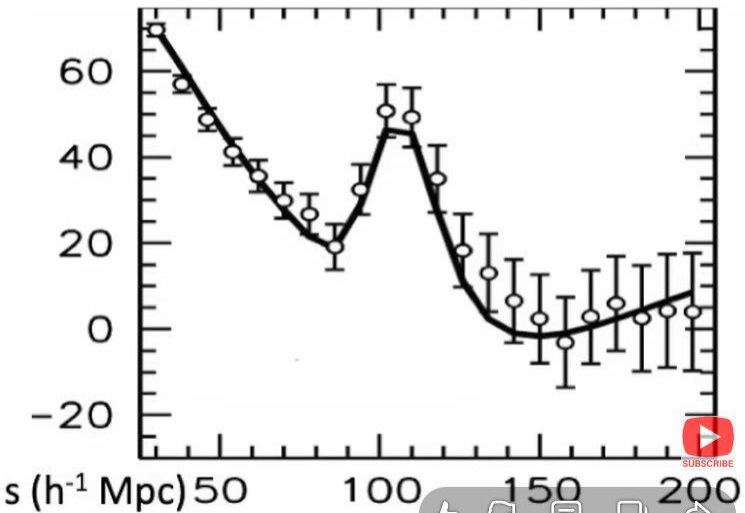
Supernovae Ia



Cosmic Microwave Background



BAO



DARK ENERGY SPECTROSCOPIC INSTRUMENT

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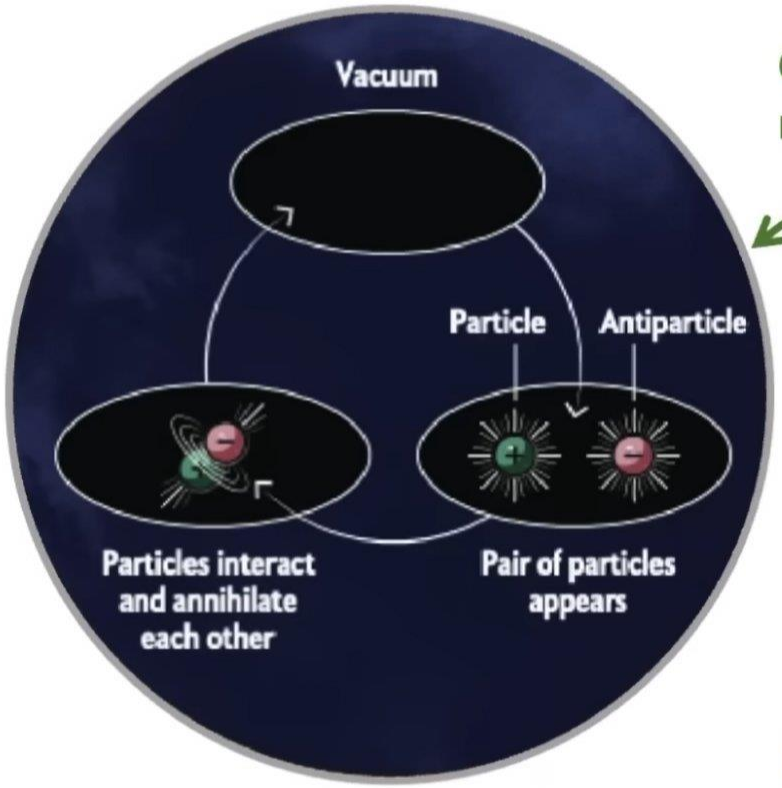
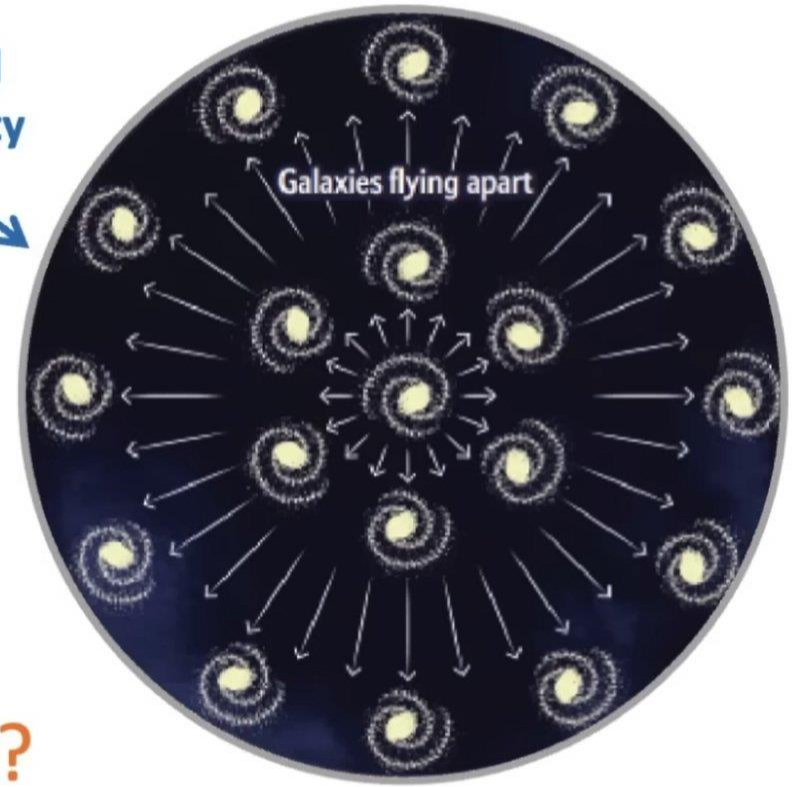
1/ Dark Energy = cosmological constant?



Quantum mechanics

Λ

General relativity



Physical origin of cosmological constant?
Related to vacuum energy?

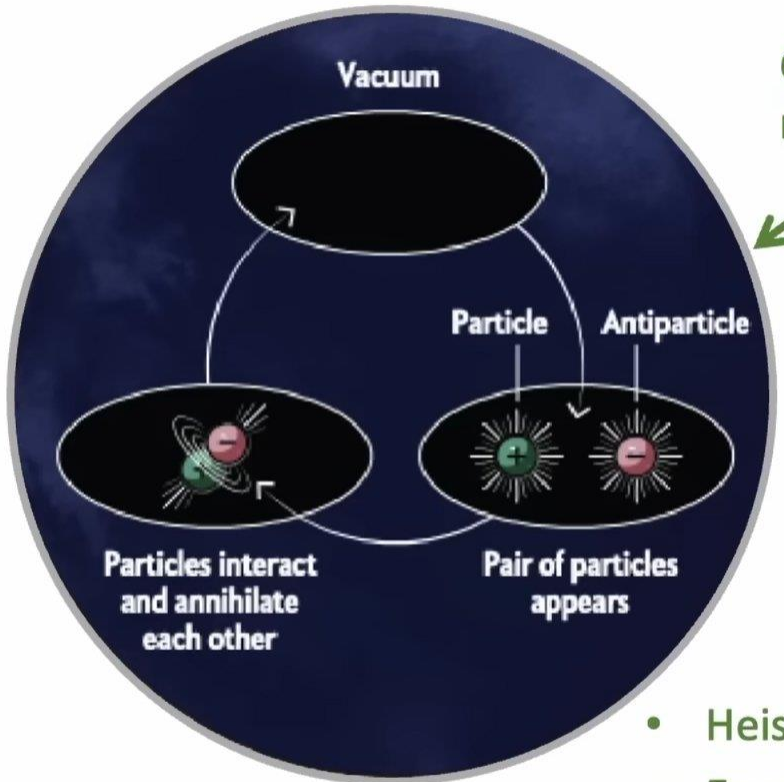
Vacuum energy

Cosmological constant

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

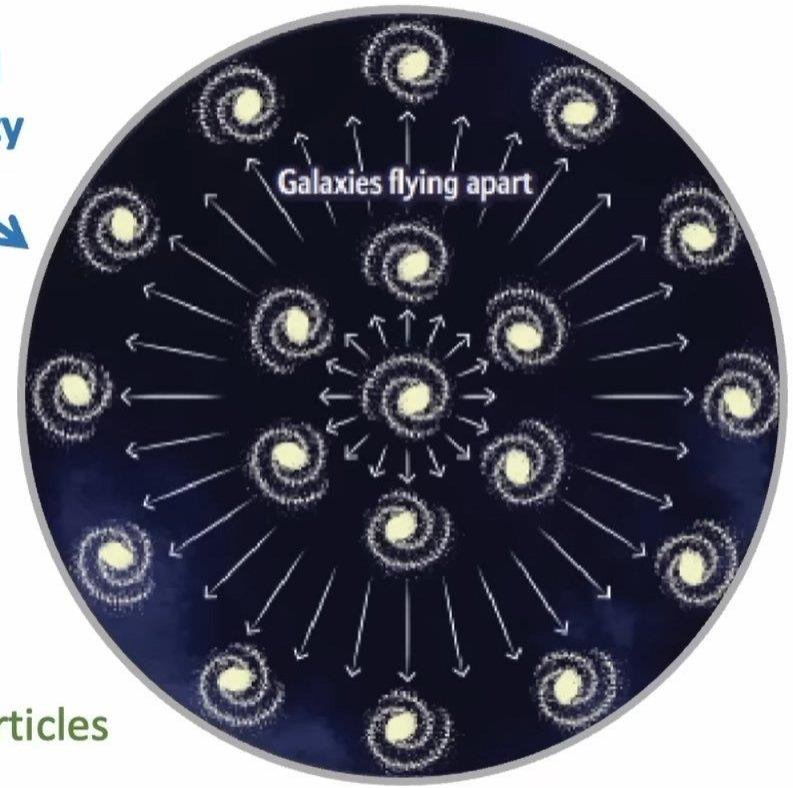
1/ Dark Energy = cosmological constant?



Quantum mechanics

Λ

General relativity



Vacuum energy

- Heisenberg uncertainty principle – vitual particles
- Energy associated to each k-mode
- Integrate over all modes up to $k_{max} = M_{pl}$
- Vacuum energy density $\rho_{vac} \sim M_{pl}^4$

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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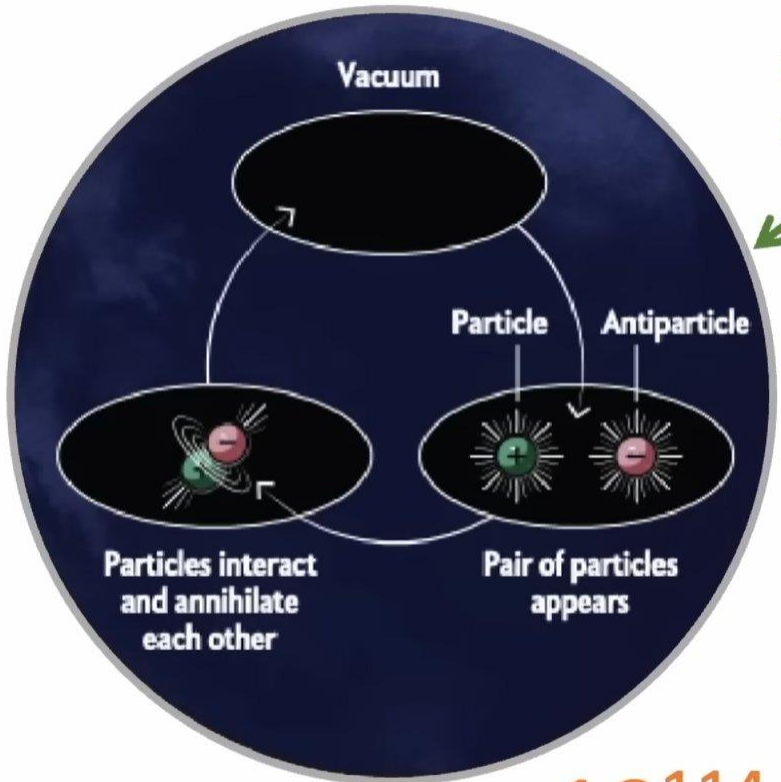
1/ Dark Energy = cosmological constant?



Quantum mechanics

Λ

General relativity

10^{114} J/m^3

Vacuum energy

Cosmological constant

- Expansion rate H
  depends on energy densities
- Dominated by dark energy today
  $H^2 = (8\pi G/3)\ \rho_{DE} = \rho_{DE} / (3\ M_{pl}^2)$
- Dark energy density ~ $H_0^2\ M_{pl}^2$

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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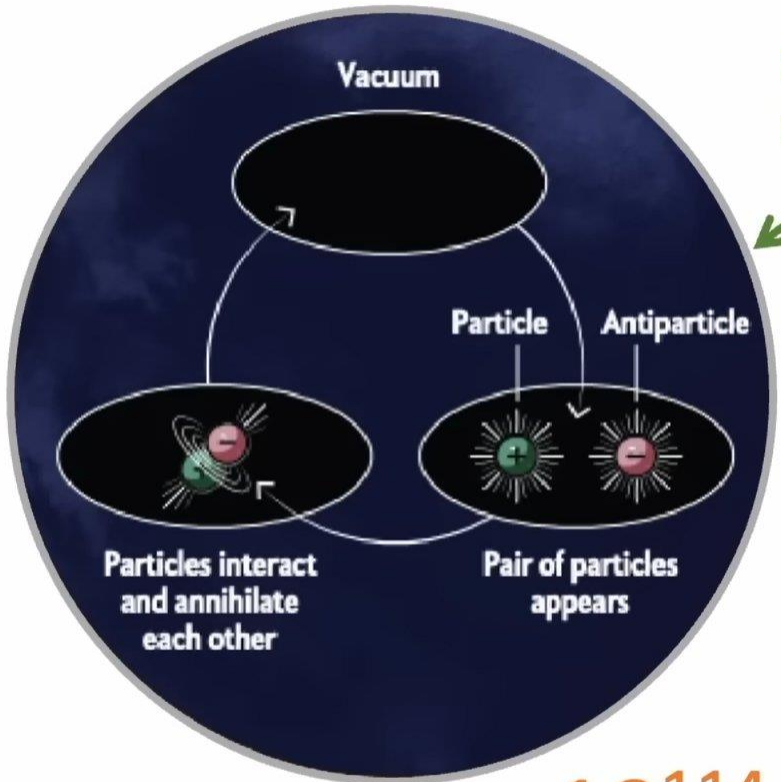
1/ Dark Energy = cosmological constant?



Quantum mechanics

Λ

General relativity

10^{114} J/m^3

Vacuum energy

10^{-9} J/m^3

Cosmological constant

1/ Dark Energy = cosmological constant?

Improved calculation of vacuum energy density

- Limit to known particles
  Masses (max ~ 100 GeV) << Planck Mass (10^{19} GeV) → 55 orders of magnitude discrepancy

- Invoke supersymmetry theory
  to each particle its supersymmetric partner
  Compensation mechanism (+ for bosons, – for fermions)
  But supersymmetry broken today, $M_{susy} > M_{known\ particles}$

quark ↔ squark

gluon ↔ gluino

neutrino ↔ sneutrino

Higgs ↔ Higgsino

Boson Z ↔ Zino

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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2/ Dark Energy = new fluid?

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Cosmological constant can be interpreted in this framework

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \longrightarrow G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu}$$

- Properties: density, pressure (negative!) $w = \frac{p}{\rho c^2}$
- Time evolution?
  - No ⟶ Possibly a cosmological constant
  - Yes ⟶ General case

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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DARK ENERGY SPECTROSCOPIC INSTRUMENT

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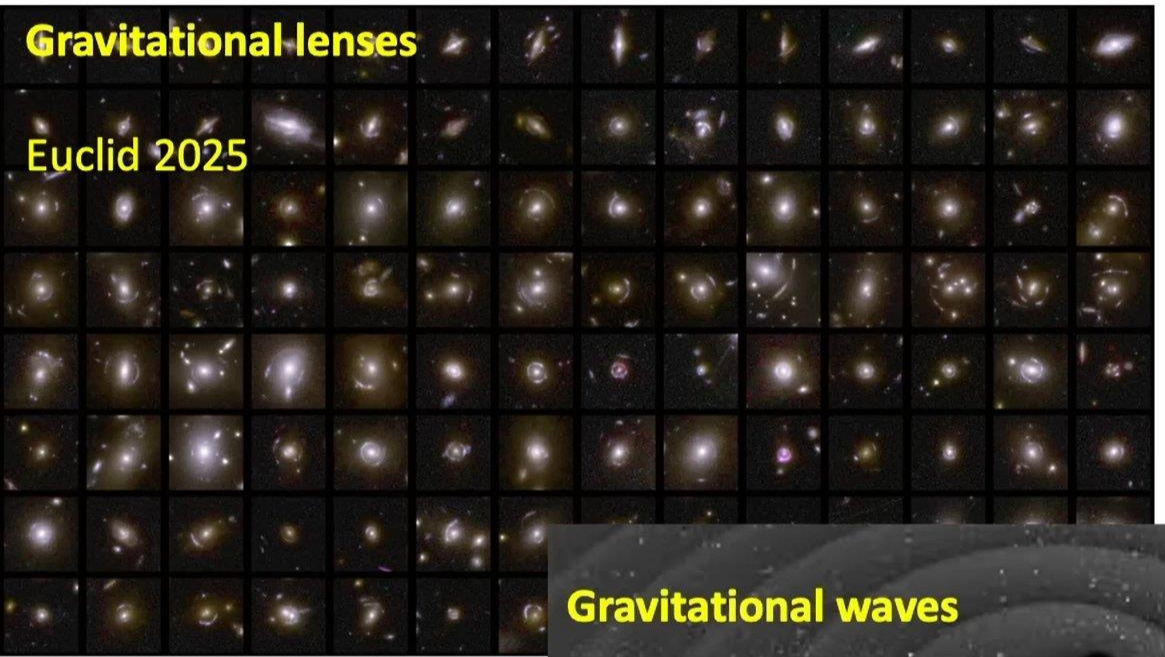
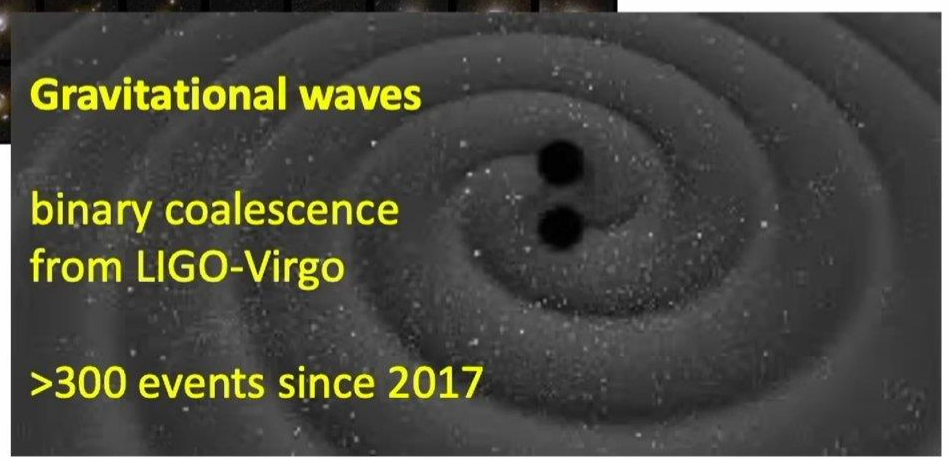
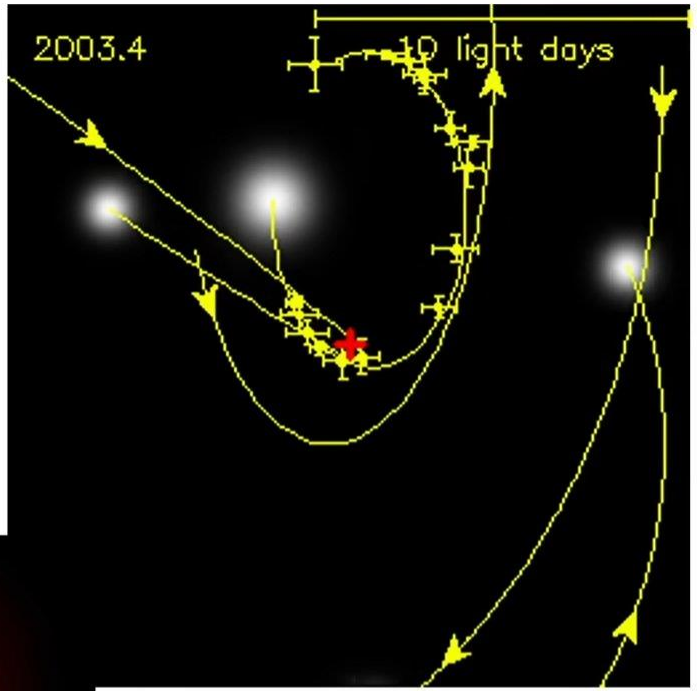
3/ Modified gravity laws?

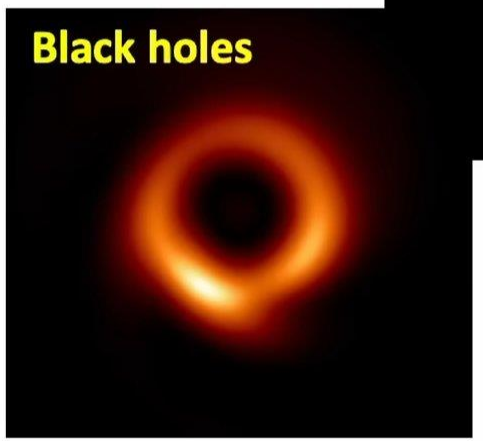
Needs to reproduce General Relativity in tested regimes





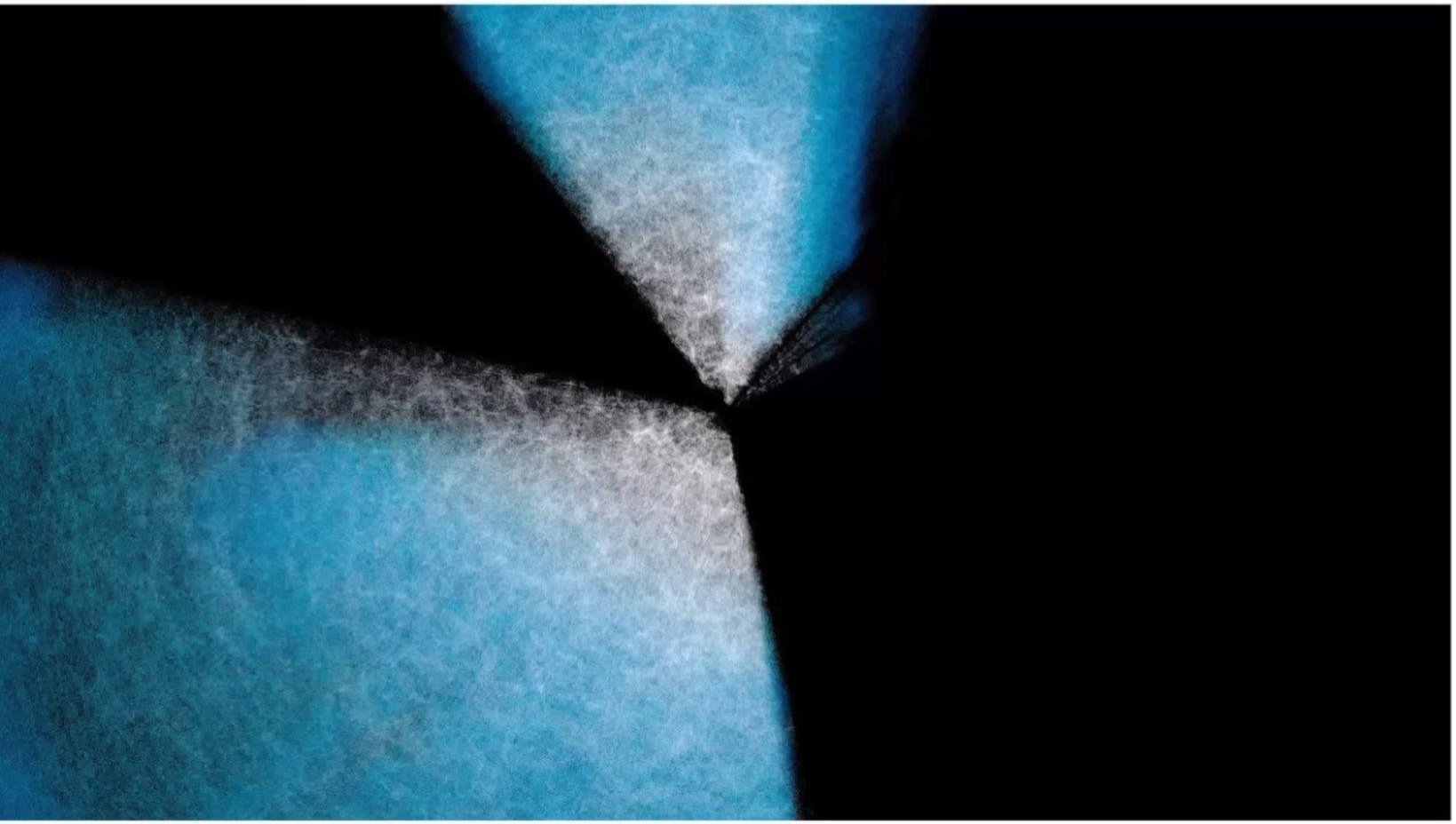


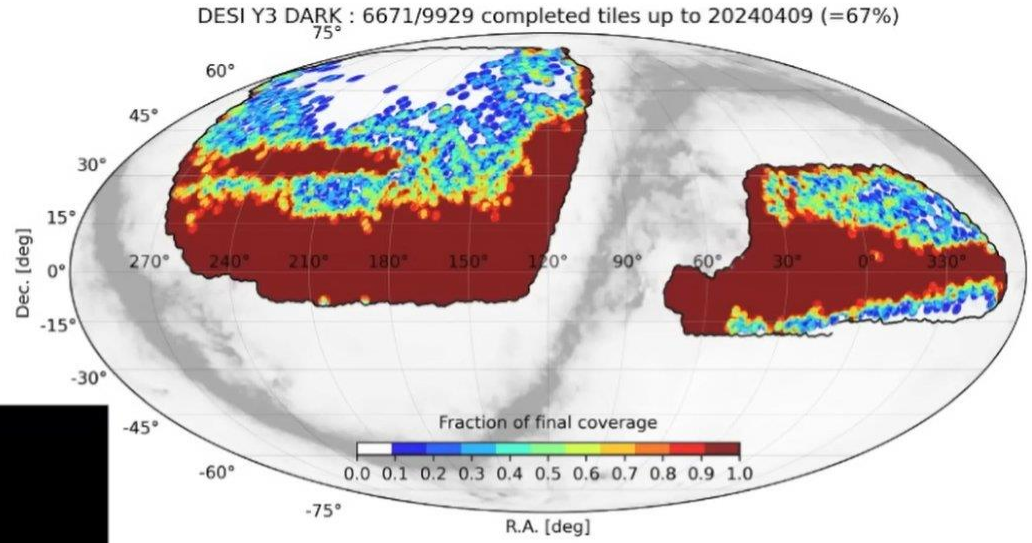
4 10^6 M_{sun} within r = 17 l.hrs
at Galactic Center
(2005)



6.5 10^9 M_{sun} in Messier 87
55 million l.yr. from Earth
(2023)

DESI data




DESI Y3 DARK : 6671/9929 completed tiles up to 20240409 (=67%)
Dec. [deg]
R.A. [deg]
Fraction of final coverage
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

2025 (DR2) analysis sample

820,000 Lyman-α forests
14.3 million galaxies and quasars

Almost 10x larger than SDSS (20 years)

DESI DR2 results I: Lya (*arXiv:2503.14739*)
DESI DR2 results II: BAO (*arXiv:2503.14738*)

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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Blinding strategy

Blinded analysis to prevent confirmation bias

- Shifts of source redshifts
- Shift of BAO peak

Procedure

Determine analysis parameters

& validate choices based on

- Blinded data
- Simulated data (*mocks*)

Robustness tests

- Variations in data vector: data splits, imaging systematics, …
- Variations in BAO measurement and modelling

DESI DR2 results I: Lya (*arXiv:2503.14739*)

DESI DR2 results II: BAO (*arXiv:2503.14738*)

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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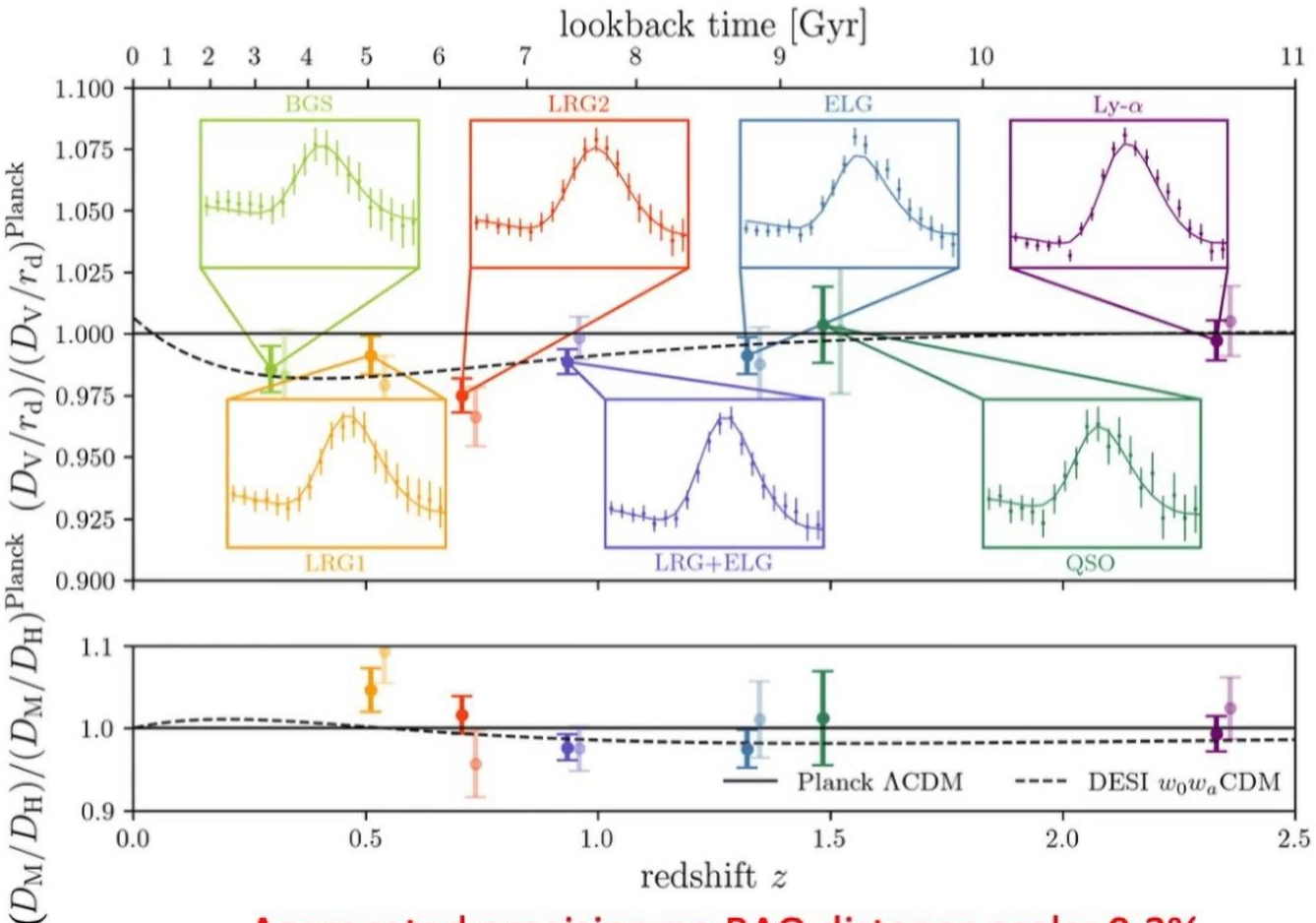
DESI BAO results

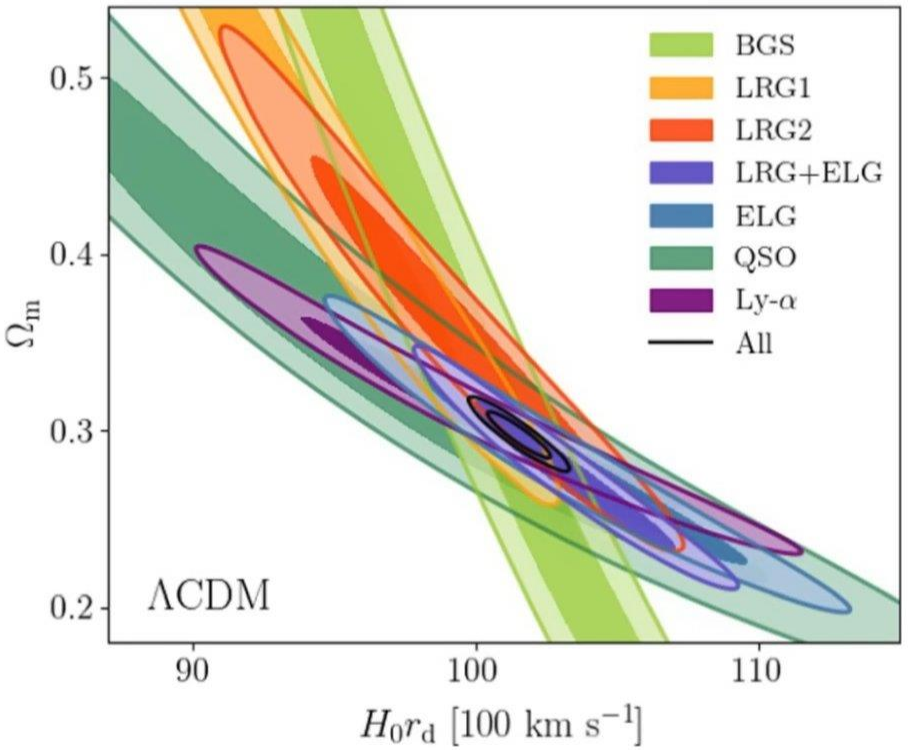
BAO data: $\Delta\theta$ and Δz ⟶ D_M / r_d and D_H / r_d

$$D_V = \left(z D_M(z)^2 D_H(z)\right)^{1/3}$$

Ω_M and $H_0 r_d$



Aggregated precision on BAO distance scale: 0.3%



Agreement & complementarity between tracers

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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Dark Energy

Equation of state $P = w\rho c^2$ (pressure, density)

Dynamic dark energy

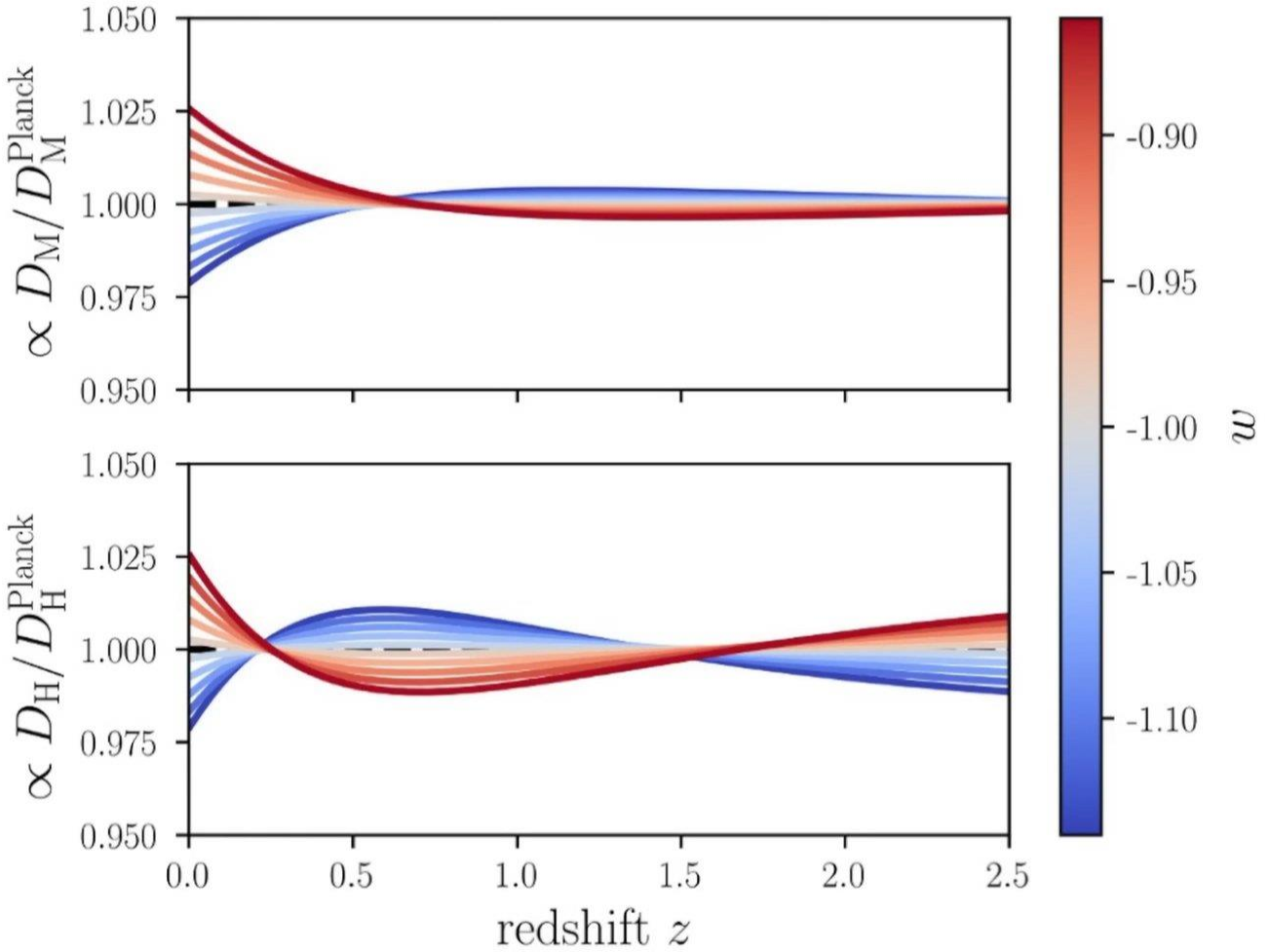
(Chevalier & Polarski 2001, Linder 2003)

$$w(z) = w_0 + w_a \frac{z}{1+z}$$

$$w(a) = w_0 + (1-a)w_a$$

Cosmological constant Λ

$$\Longrightarrow \; w_0 = -1 \text{ and } w_a = 0$$



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DARK ENERGY SPECTROSCOPIC INSTRUMENT

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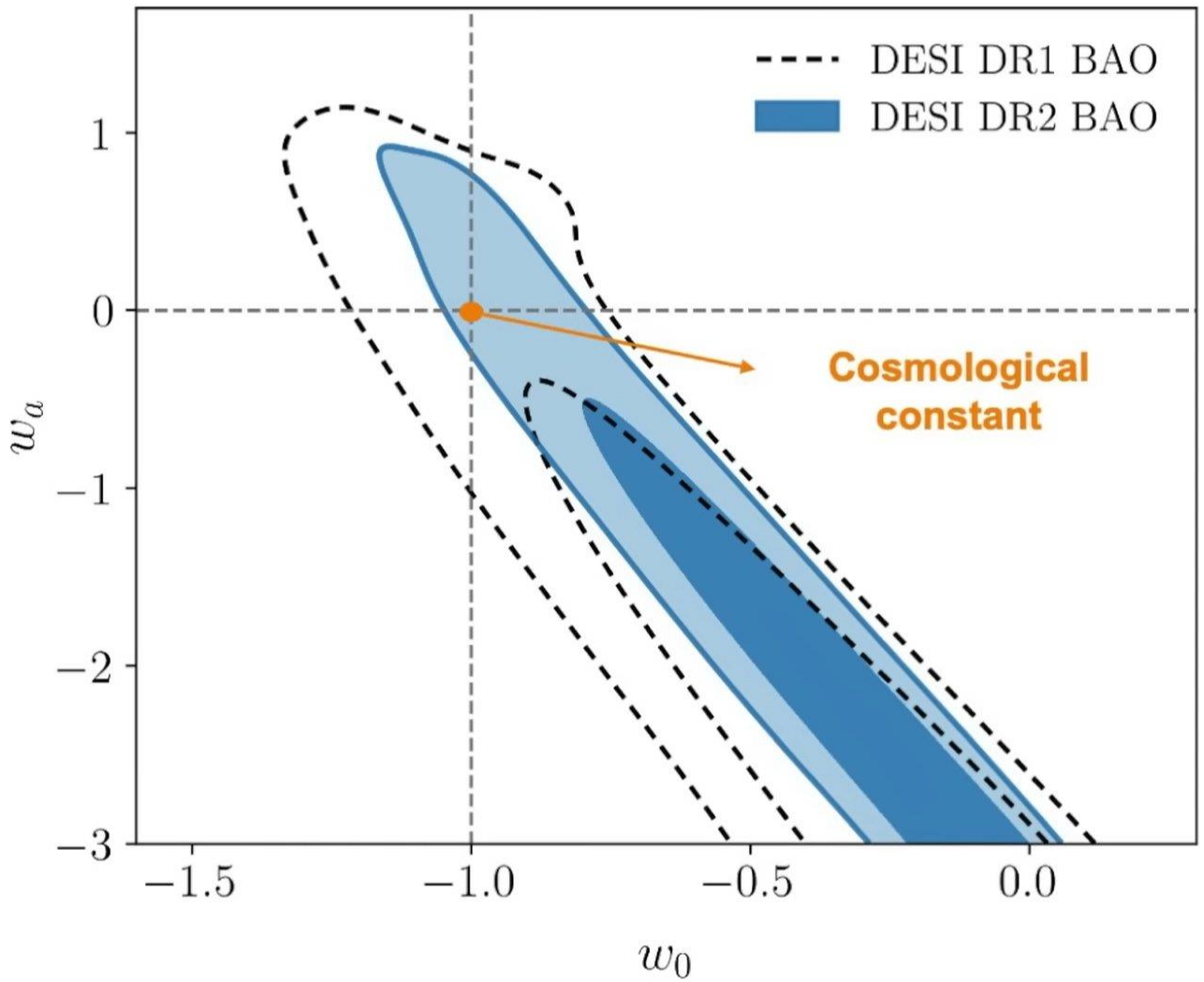
Evolving Dark Energy

$$w(a) = w_0 + (1-a)w_a$$

- DESI DR2 within 2σ of **ΛCDM**
- *But not same ΛCDM as CMB data*
  (2.3σ tension with Planck)



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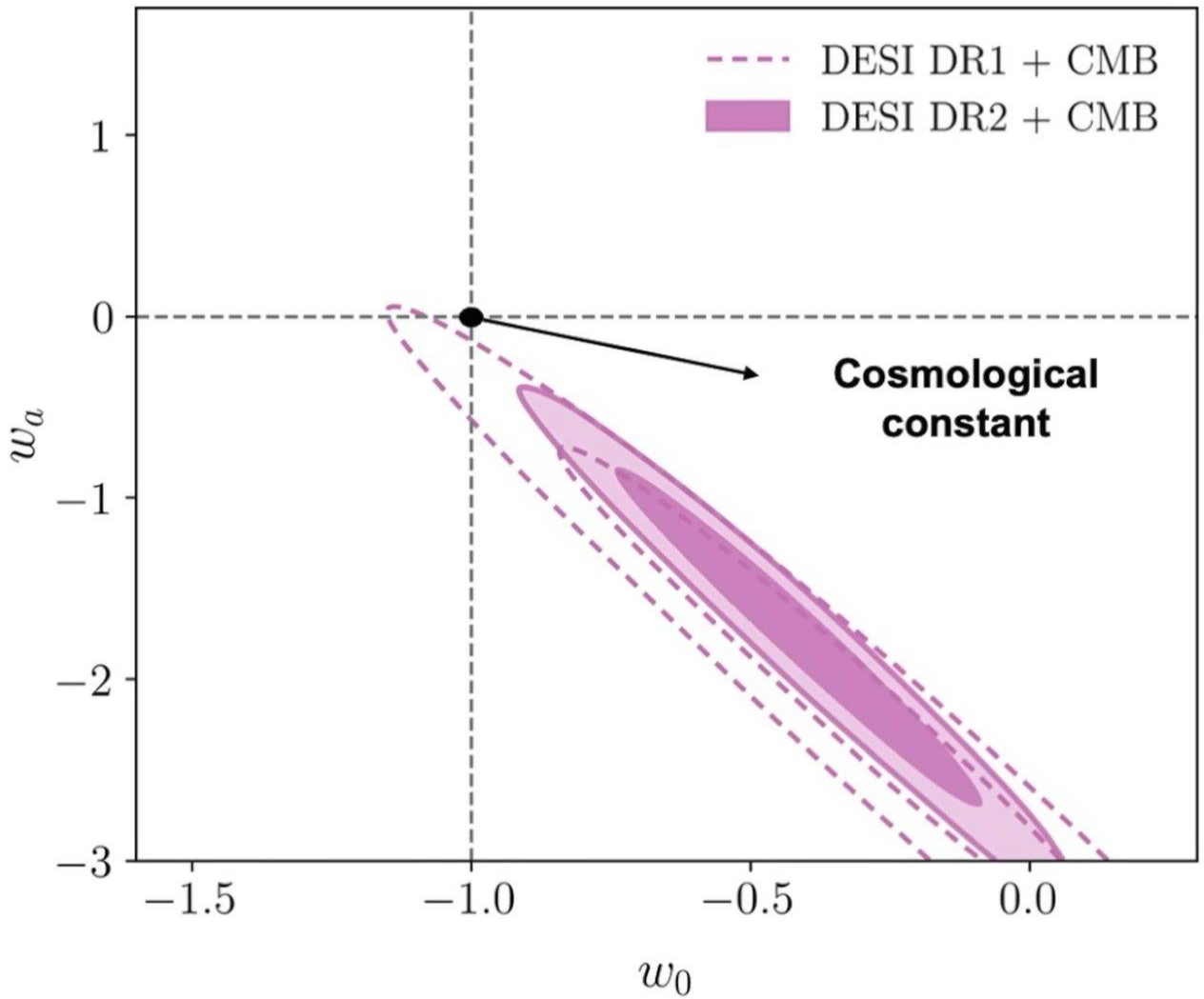
Evolving Dark Energy

$$w(a) = w_0 + (1-a)w_a$$

- **3.1σ** preference for evolving dark energy with **DESI + CMB**[1]

1. primary CMB: Planck PR4
2. CMB lensing: Planck PR4 + ACT DR6



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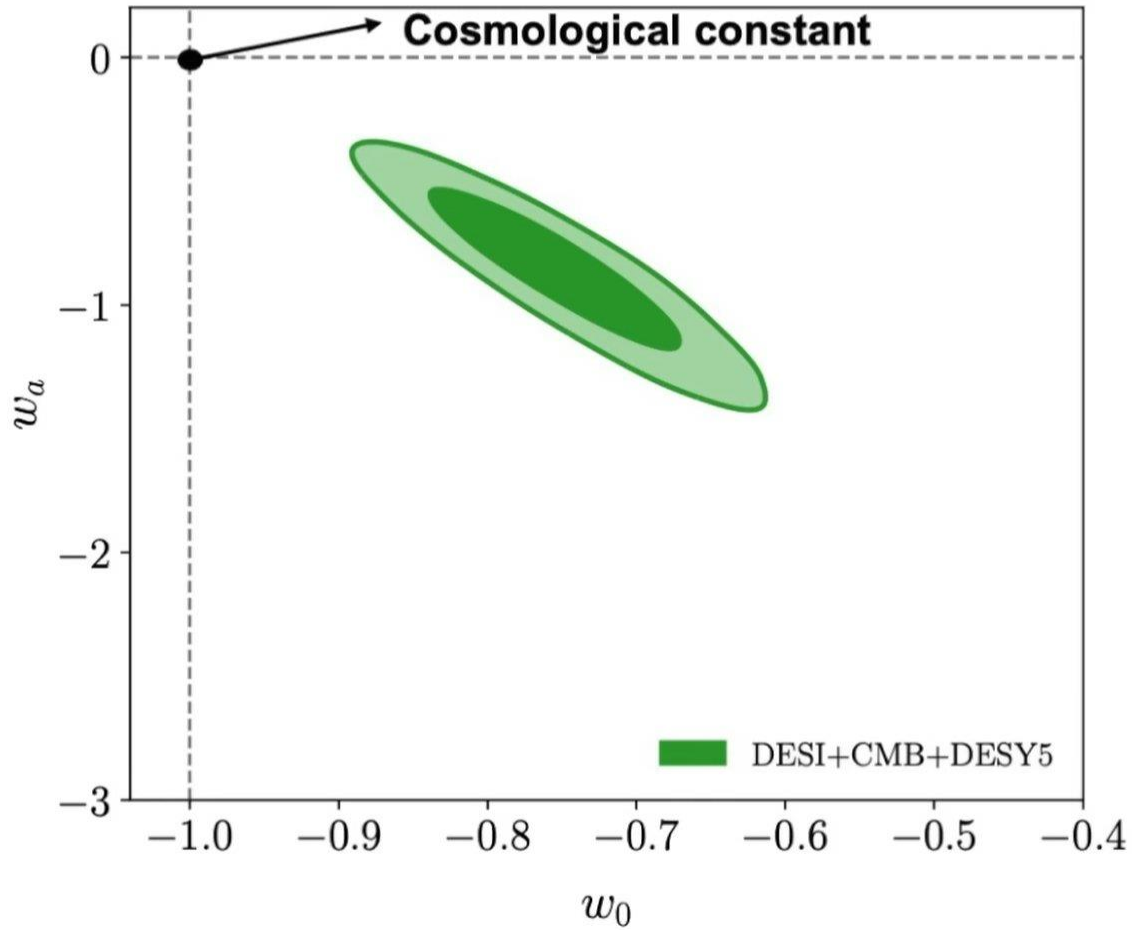
Evolving Dark Energy

$$w(a) = w_0 + (1-a)w_a$$

- **4.2σ** preference for evolving dark energy with **DESI + CMB + SN***



* **3.2σ** preference with re-analysis of DES-Y5 SN data

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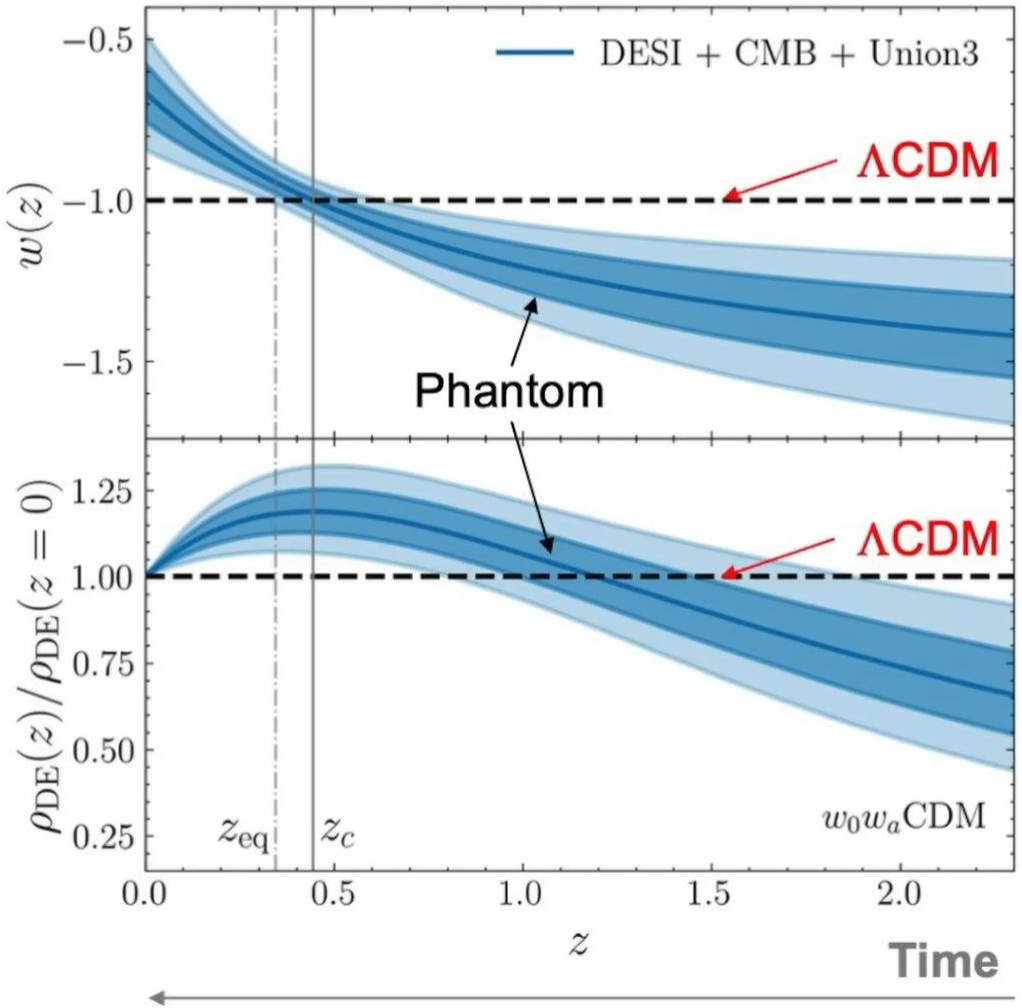
Dark energy model

DESI DR2 results II: BAO (*arXiv:2503.14738*)

DESI supporting paper Lodha+ (*arXiv:2503.14743*)



w < -1 at high z :
dark energy density increases with time!

⟹ Complex dark sector?

Maximum dark energy density
(phantom crossing)
reached at $z \sim 0.45$
(~5 billion years ago)

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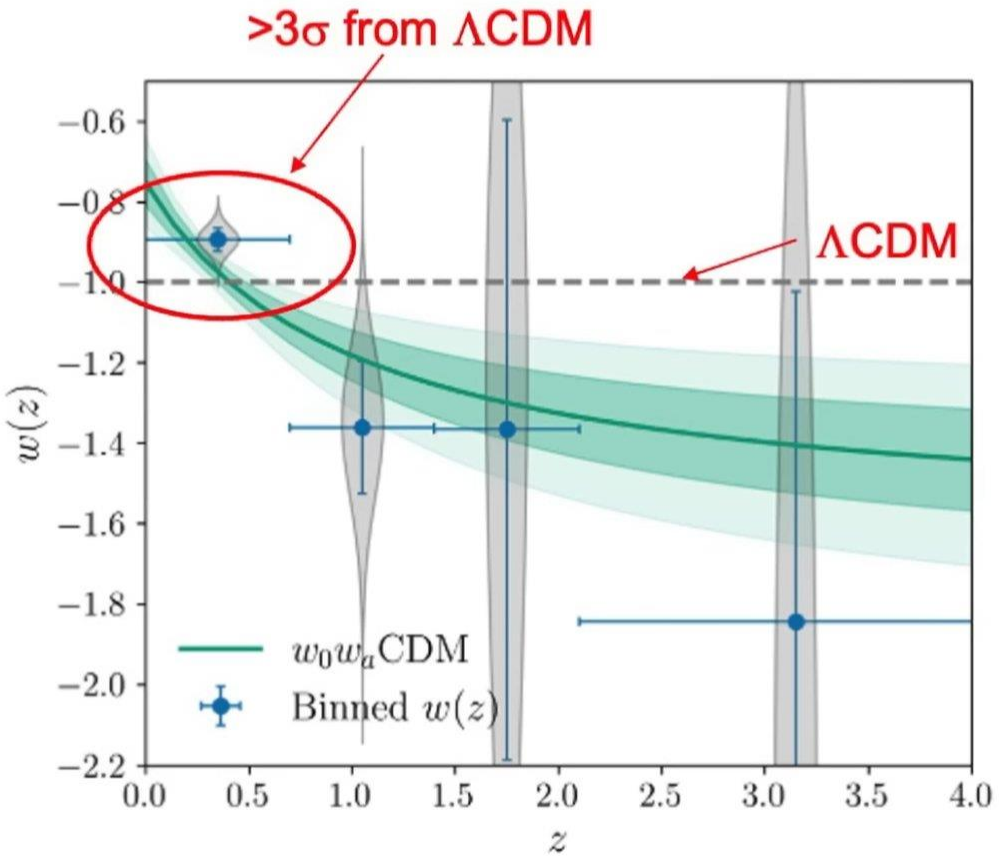
Dark energy model

DESI DR2 results II: BAO (*arXiv:2503.14738*)

DESI supporting paper Lodha+ (*arXiv:2503.14743*)

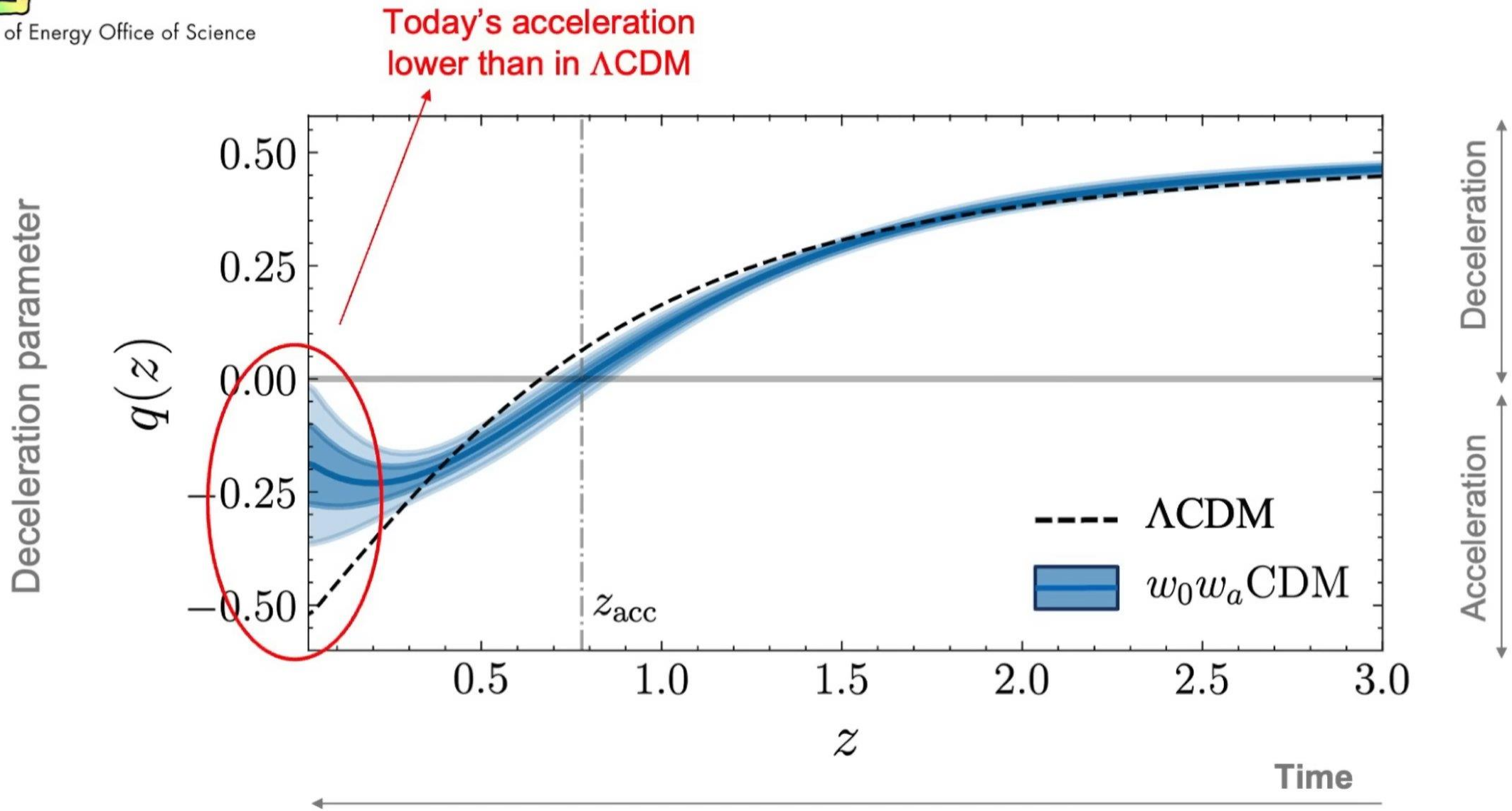


Binned reconstruction of $w(z)$

- Consistent with w_0w_aCDM
- Weaker than ΛCDM at small z (>3σ)
- Preference for ”phantom” at large z

Weakening dark energy

DESI DR2 results II: BAO (*arXiv:2503.14738*)
DESI supporting paper Lodha+ (*arXiv:2503.14743*)



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In conclusion, why all the fuss?

- Dark Energy is the **biggest mystery** in cosmology today
- Dark energy is a big thing!
  Universe **2x bigger** today (in volume) than if only made of matter
- **Evolving dark energy** would be a revolution!
  ΛCDM has been considered to be the standard model of cosmology for two decades

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